

# Electron Cooling at FNAL

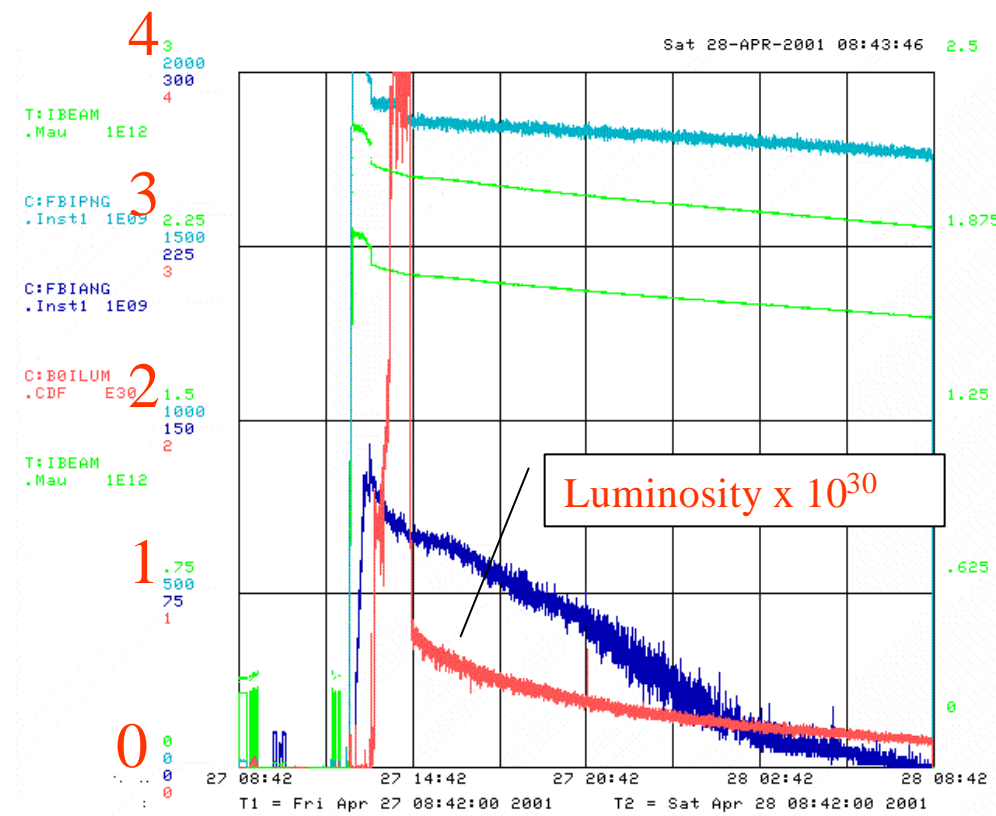
Sergei Nagaitsev, Fermilab  
Snowmass 2001

# Tevatron Collider Luminosity Goals

- The luminosity goal for Run IIa is  $2 \text{ fb}^{-1}$ 
  - Initial operation: 36p x 36pbar
  - Peak luminosity up to  $2 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$
  - Switch to 103 bunches at  $1 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$
  - Length of Run IIa is about 2 years
- The luminosity goal for Run IIa+ Run IIb is  $15 \text{ fb}^{-1}$ 
  - Increase antiproton intensity by 2- 3
  - Peak luminosity up to  $5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$
  - 103 bunch operation
  - Length of Run IIb is about 4 years

# Run II preparations

- Initial luminosity goal for Run II is  $8 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ .
- Had several successful engineering runs with a 36-bunch operation.
- Saw  $8 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$  with 5 times fewer protons and 10 times fewer antiprotons, as compared to initial Run II parameters.



Time on Apr. 27, 2001, 24 hours total

# Beam Cooling in the Recycler

The missions for any cooling system in the Recycler are:

- Transverse and longitudinal emittances of the recycled antiprotons need to be reduced by  $1/e$  in the 6-7 hour store length.
- Momentum spread of stacked antiprotons needs to be reduced between transfers from the Accumulator to the Recycler.

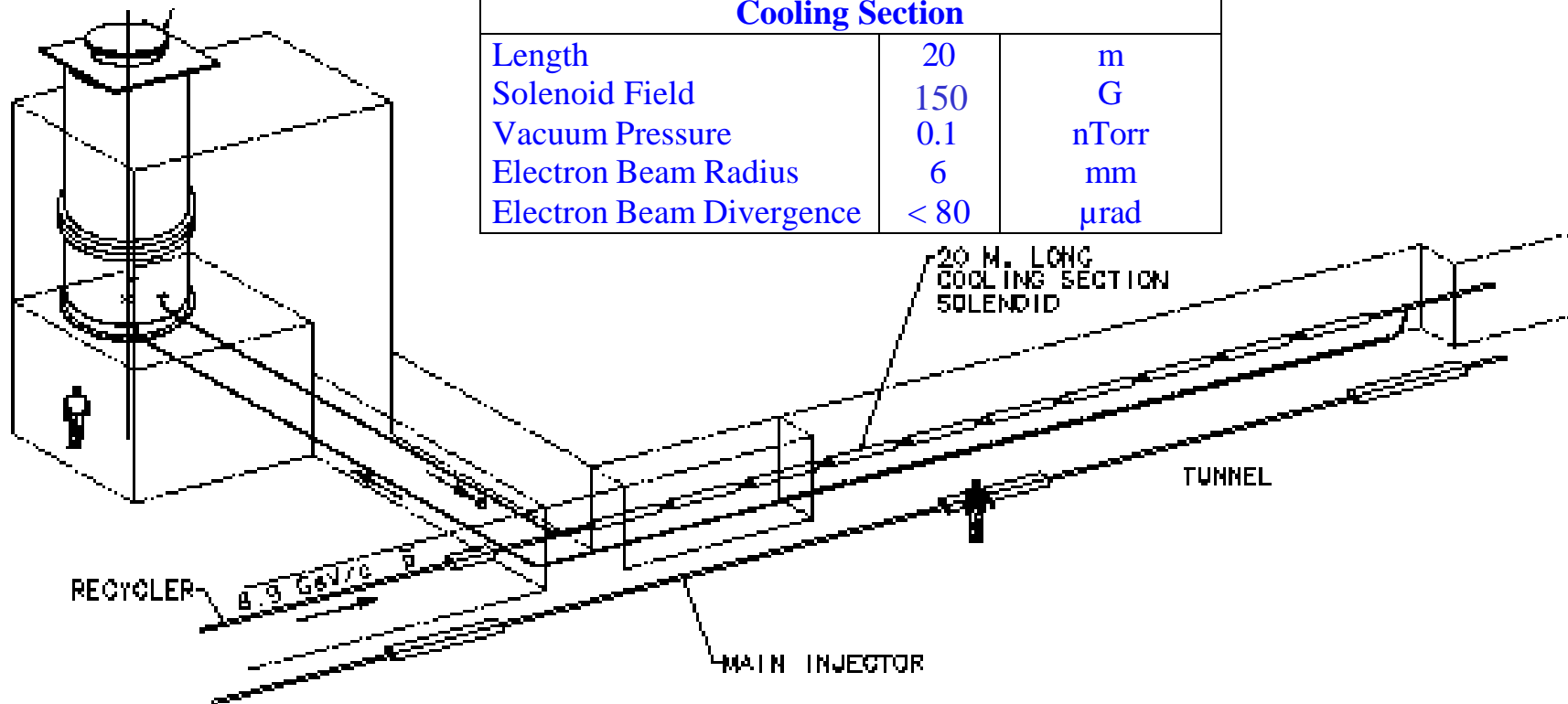
# High Energy Electron Cooling

- I define a “high energy” as the energy where the conventional technology to produce and transport electrons becomes difficult to use. These technologies are:
  - Power supply (or energy source);
  - Continuous magnetic field of 1 kG or more;
  - Short cooling section (about 2 m).
- This probably corresponds to  $g > 1.5$
- Well understood fundamentals but much R&D is needed.
- At present, only Fermilab has committed funds to do a full-scale R&D for a system to cool 8.9 GeV/c antiprotons.

# Schematic Layout of the Fermilab's Recycler Electron Cooling

Electron Cooling System Parameters

| Parameter                        | Value | Units     |
|----------------------------------|-------|-----------|
| <b>Electrostatic Accelerator</b> |       |           |
| Terminal Voltage                 | 4.3   | MV        |
| Electron Beam Current            | 0.5   | A         |
| Terminal Voltage Ripple          | 500   | V (FWHM)  |
| Cathode Radius                   | 2.5   | mm        |
| Gun Solenoid Field               | 600   | G         |
| <b>Cooling Section</b>           |       |           |
| Length                           | 20    | m         |
| Solenoid Field                   | 150   | G         |
| Vacuum Pressure                  | 0.1   | nTorr     |
| Electron Beam Radius             | 6     | mm        |
| Electron Beam Divergence         | < 80  | $\mu$ rad |



# Fermilab R&D program in high energy electron cooling.

- The mission of the cooling system at Fermilab is too provide faster antiproton stacking rates (together with the stochastic cooling system).
- The only fully funded R&D program in HEEC to date.
- The choice of a commercial HV power supply (Pelletron) required non-standard approach to electron beam optics.
- Low magnetic field strength (150 G) in the cooling section was chosen. As a consequence the Coulomb log is high, but the required transverse electron temperature is very low: 0.2 eV.
- The approach is probably suitable for energies of up to 8 MeV

# Electron Cooling R&D

## Project Goals

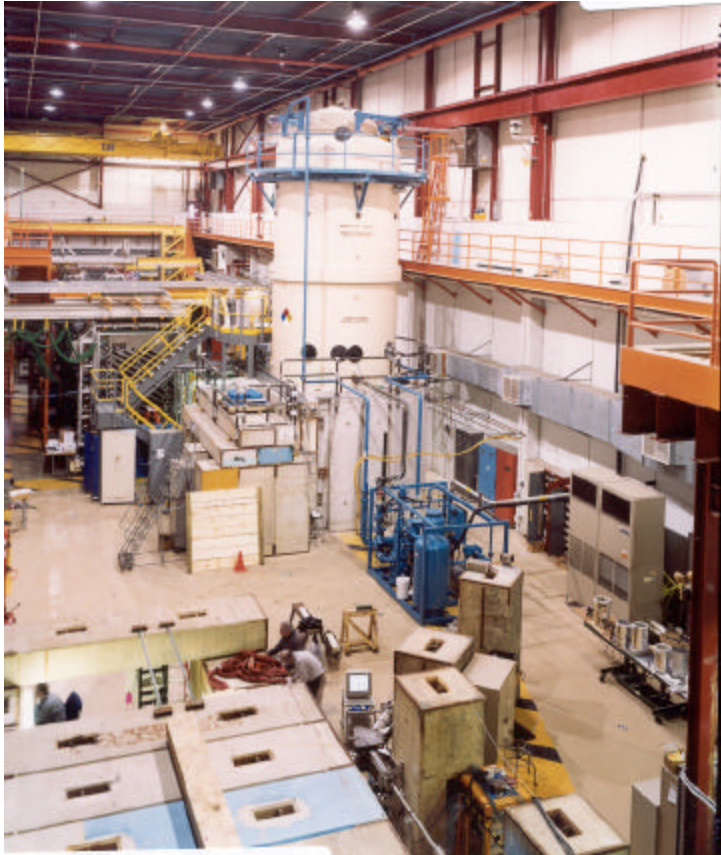
- Electron beam current 0.5 A
- Electron beam kinetic energy 4.3 MeV
- Beam angular spread (cooling section) 80  $\mu$ rad
- Energy spread (FWHM) 500 eV
- Pressure (cooling section)  $1 \times 10^{-10}$  Torr
- Typical time between crashes 1 hour
- Crash recovery time 5 min
- Typical time between tank openings 1 month (initial)  
6 months (final)



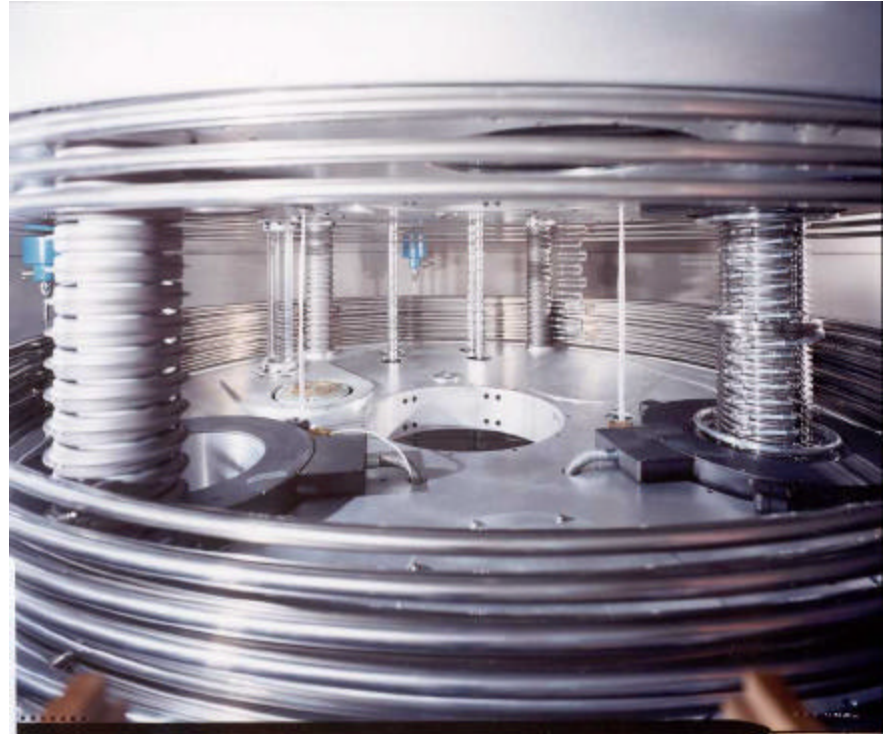
# Project issues to be covered in this talk

- Pelletron commissioning and beam recirculation tests
- Novel beam transport scheme
- Cooling section solenoid
- Installation plans

# Fermilab Electron Cooling R&D Facility



5 MV Pelletron installed



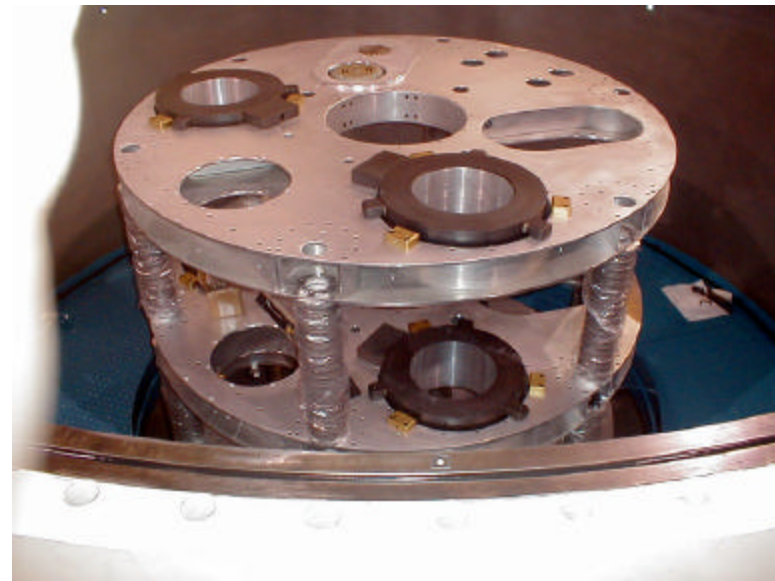
High-voltage column with grading hoops partially removed to show the accelerating tube (right) and the charging chains (far center).

S. Nagaitsev, FNAL

# Fermilab Electron Cooling R&D Facility



The Pelletron tank is accessed through a manway.



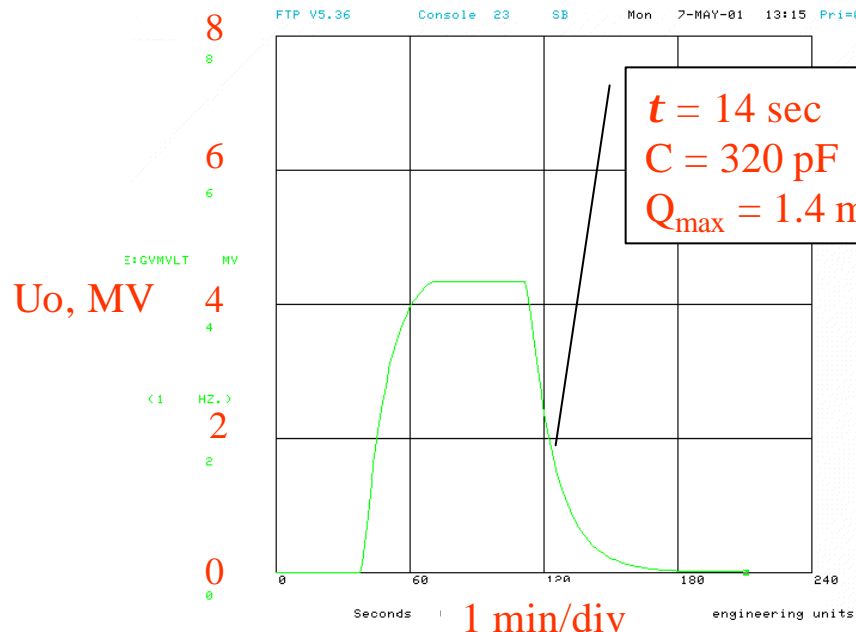
Structure inside the tank -- separator boxes and beam lenses. No beam tubes were installed at the time of this photo.

S. Nagaitsev, FNAL

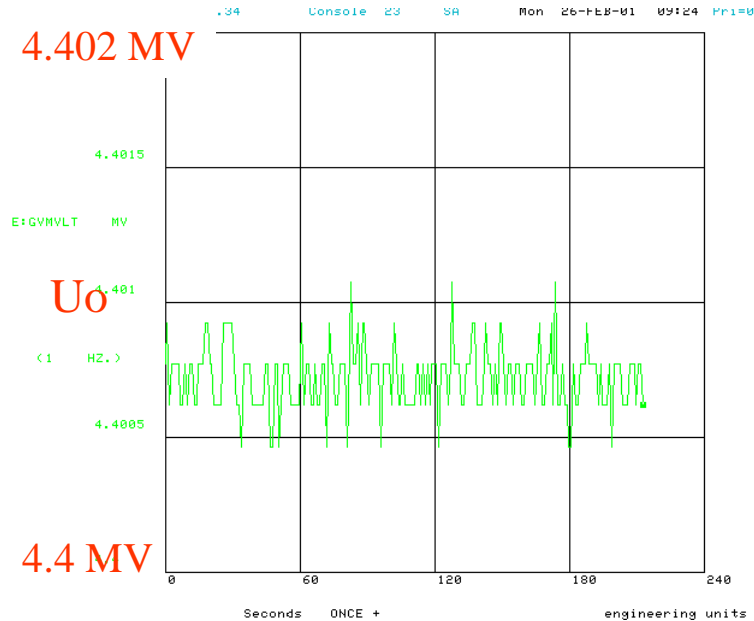
# Pelletron commissioning

- The 5 MV Pelletron has been installed and commissioned. While filled with SF<sub>6</sub> (no vacuum tubes) at 5.5 atm the Pelletron reached more than 6 MV, thus, no HV problems on the gas side are expected.
- Because of the large amount of energy (3 kJ) stored in the HV terminal and its potential for damage, the HV conditioning of vacuum tubes is performed with the help of shorting rods, one 1-MV section at a time. Each section (out of 5) was conditioned separately to 1.2 MV. The Pelletron with tubes was then conditioned to 4.8 MV. We think this will improve with time.
- The recirculation of a 0.4-mA beam was demonstrated. The electron gun performed to specs. All beam line elements worked.

# Charging and voltage regulation

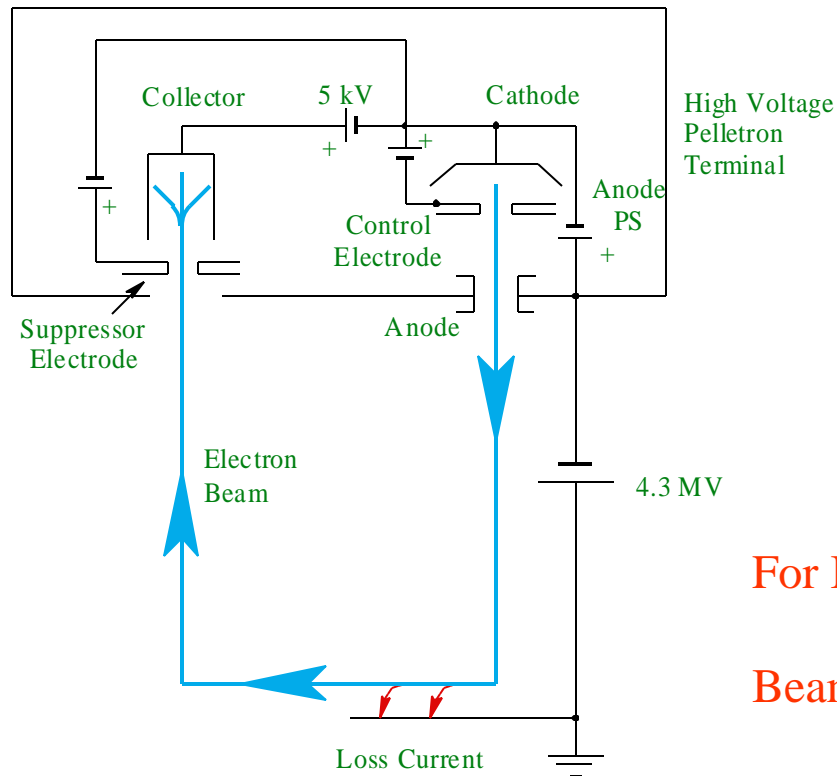


Pelletron charging with a voltage regulation system ON. After about 1 min the charging system was turned OFF and the terminal was discharged through resistive dividers.



Terminal voltage in a regulation regime: 500 V/div, 1 min/div.  
Required voltage for the Recycler cooling: 4.36 MV.

# Simplified schematic of beam recirculation



For  $I = 0.5 \text{ A}$ ,  $\Delta I = 5 \mu\text{A}$ :

Beam power 2.15 MW

Current loss power 21.5 W

Power dissipated in collector 2.5 kW

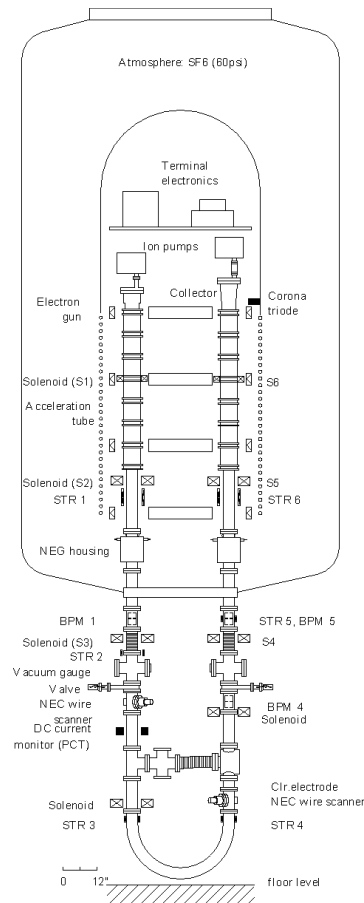
# Electron Cooling Proof-of-Principle (Recirculation experiment)

## GOAL

- To demonstrate a 0.2 A recirculation for 1 hour using an existing 2 MeV Pelletron at NEC

## HISTORY

- Nov. 95: project started
- Jan. 97: first recirculated current (10  $\mu$ A)
- May 97: new gun and collector are installed
- Dec. 97: Max. recirculated current of 0.2 A
- May 98: 0.2 A for 1 hour
- Sep. 98: 0.2 A for 5 hours
- Dec. 98: Max. current of 0.7 A
- Jan. 99: Gun solenoid (200 G) installed
- Feb. 99: 5 MeV Pelletron ordered
- May.99: 0.9 A with 200 G at the cathode

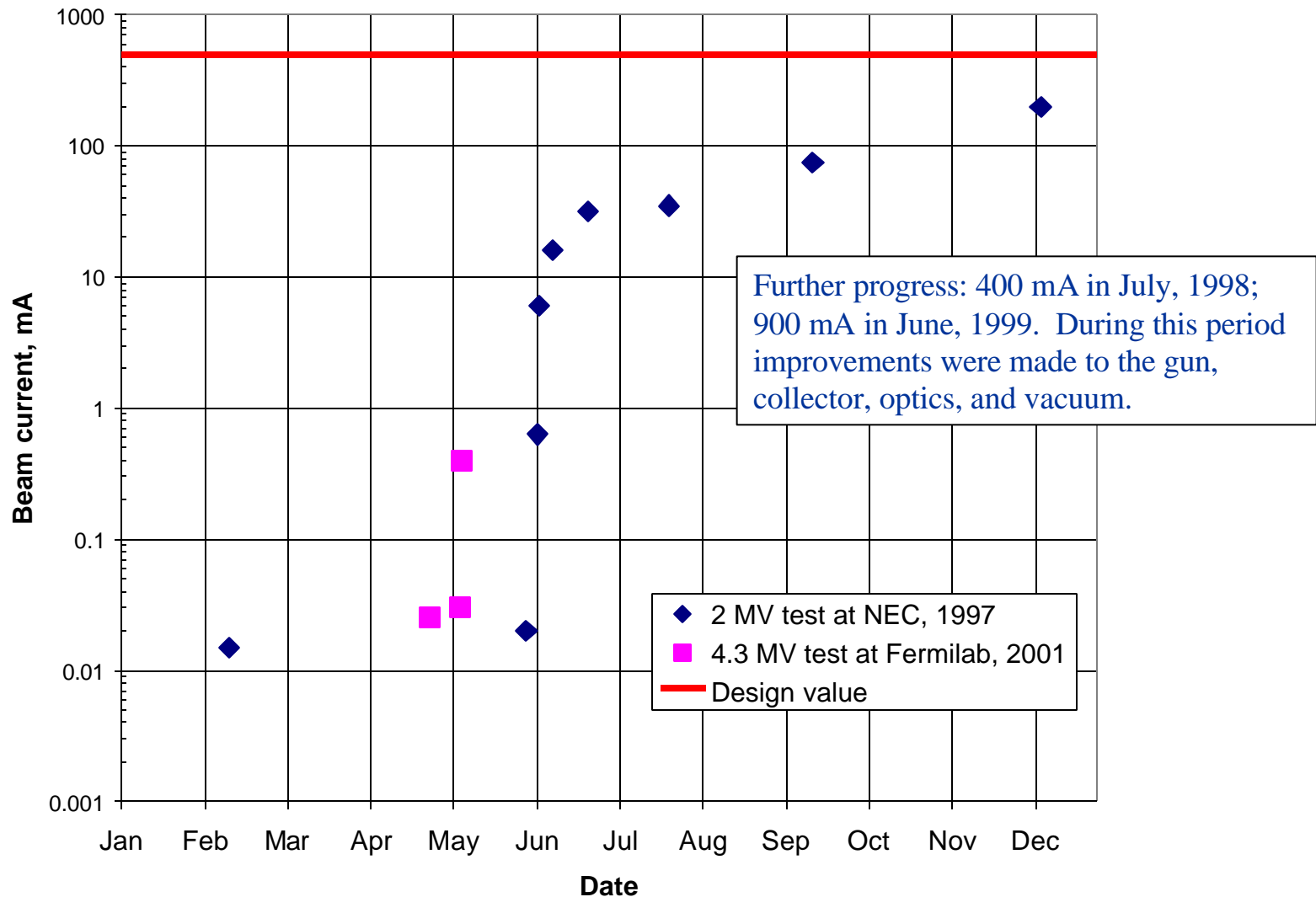


S. Nagaitsev, FNAL



# Attained recirculation currents

Max. attained beam current (1 min. or more)  
during initial operations



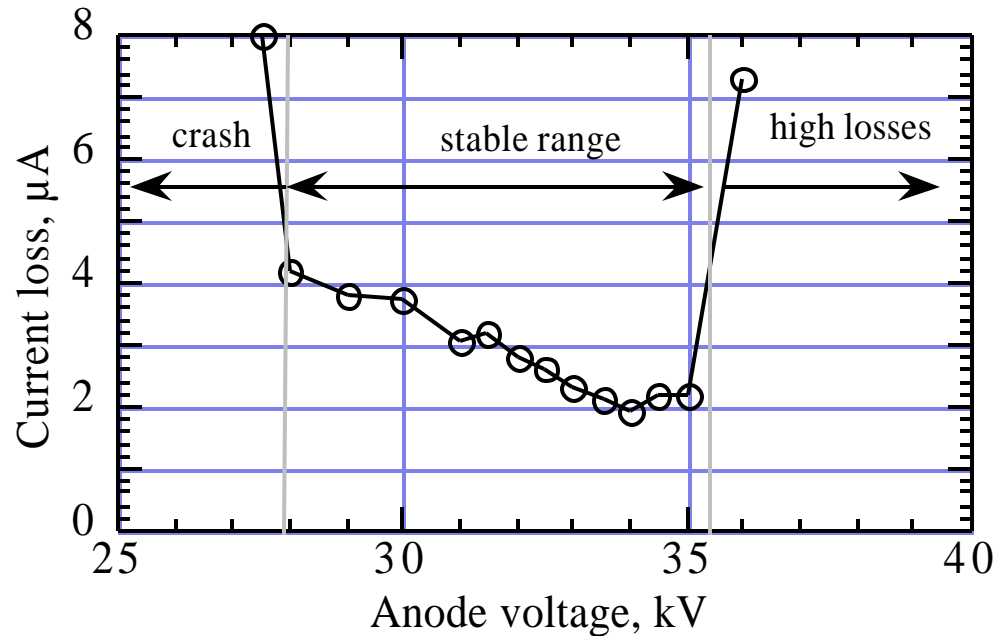
S. Nagaitsev, FNAL



# What determines the rate of progress in beam current increase?

- Duty cycle of the machine operation: HV voltage sparks damage electronics in the terminal. A typical shutdown for a repair is one week (initially). Also, there is a factor of twenty more energy stored in the Pelletron now compared to what it was during NEC tests -- thus, potentially more destruction per spark. We anticipate that the breakdowns will determine the rate of our progress.
- After all electronics is fixed and reliability is improved the rate of progress is determined by outgassing of the collector surface: initially the surface needed to be exposed to about 1 (mA/cm<sup>2</sup>)-hour dose. At this dose, the outgassing rate drops to 10<sup>-3</sup> molecule/electron -- acceptable for an operation with a 0.5-A beam current. The collector we are using now has been outgassed on a test bench and it was kept under vacuum. We anticipate this process to be less of a hindrance for us now.

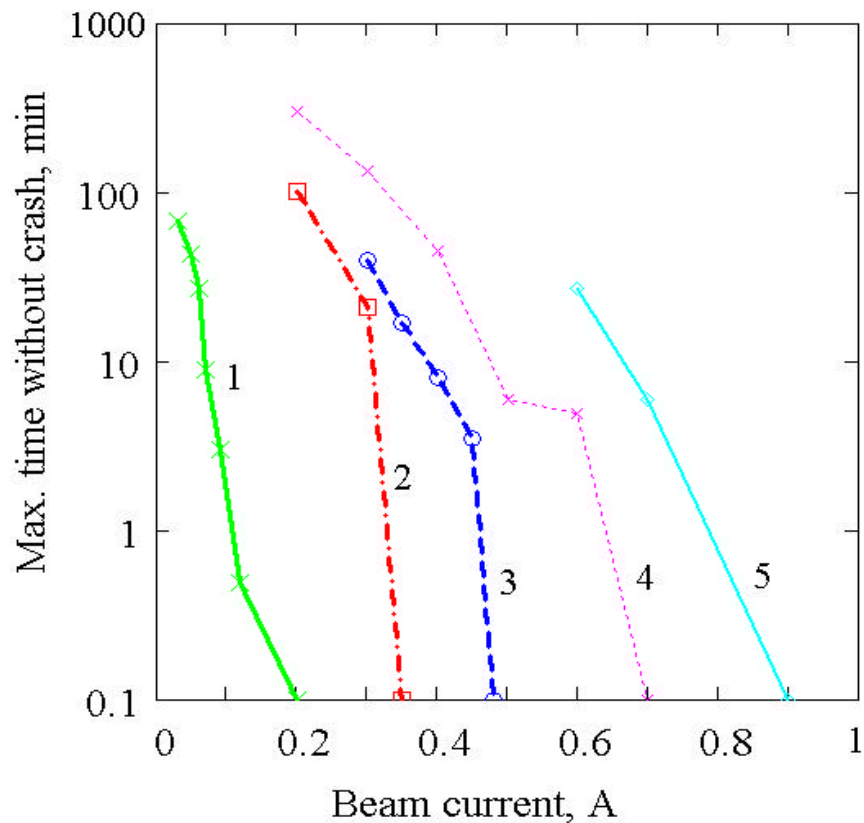
# Stability



Measured dependence of losses on beam energy. Pelletron voltage was kept at  $U_o=1.135$  MV, beam current was 200 mA. Beam kinetic energy is  $eU_o + eU_A$ .  $P=1\cdot 10^{-7}$  Torr.

“**Crash**” means a transition from a stable beam recirculation to a state with a low Pelletron voltage, when the potential along the acceleration tube is significantly redistributed and the beam current goes mainly to the gun anode.

# Stability of operation (NEC tests, 1998-99)



|   | symbol  | $Z_{\text{diaph}}$ , mm | $P, 10^{-7}$ Torr | $B_{\text{cath}}$ , G | $D_{\text{cath}}$ , mm |
|---|---------|-------------------------|-------------------|-----------------------|------------------------|
| 1 | cross   | no                      | 1                 | 0                     | 3.4                    |
| 2 | square  | 65                      | 1                 | 0                     | 3.4                    |
| 3 | circle  | 33                      | 1                 | 0                     | 3.4                    |
| 4 | cross   | 33                      | 0.2               | 0                     | 3.4                    |
| 5 | diamond | 33                      | 1                 | 200                   | 5.08                   |

Maximum recirculation time without a crash as a function of beam current for different gun designs.

# Remarks about the current recirculation setup at Fermilab

- The Pelletron voltage is higher than it was during our initial tests. Thus, additional difficulties will be associated with a higher stored energy and higher radiation.
- Vacuum needs to be better ( $10^{-9}$  Torr). The acceleration tubes are baked.
- The cathode is placed in a higher magnetic field: up to 600 G instead of 200 G. Two separate solenoids on the gun side and one solenoid on the collector side are installed.
- Motors in the tank have lower AC fields and are placed further away from the beam line. If needed, they can be mounted outside of the tank.

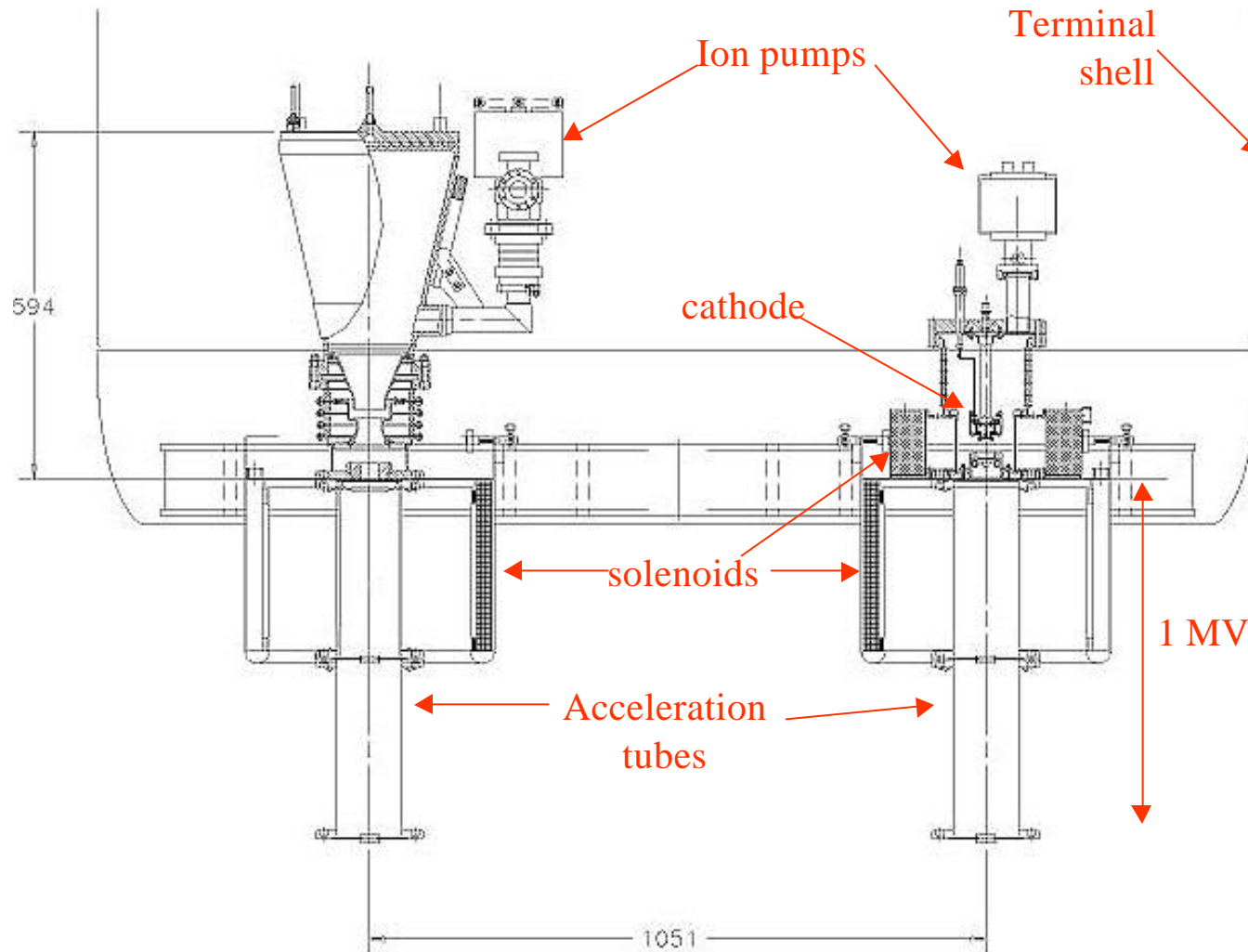
## Remarks about the current recirculation setup at Fermilab (continued)

- We anticipate that we will reach a level of 10 mA fairly quickly. Our plan is to reach 500 mA by the end of this year.
- We are planning to test every type of diagnostics on a short U-bend setup.
- We are also planning to perform tests on a slow beam position feedback system. In the future full scale beam line this will work together with the NMR-based magnet stabilization and the dispersionless beam transport line.

# Beam transport line

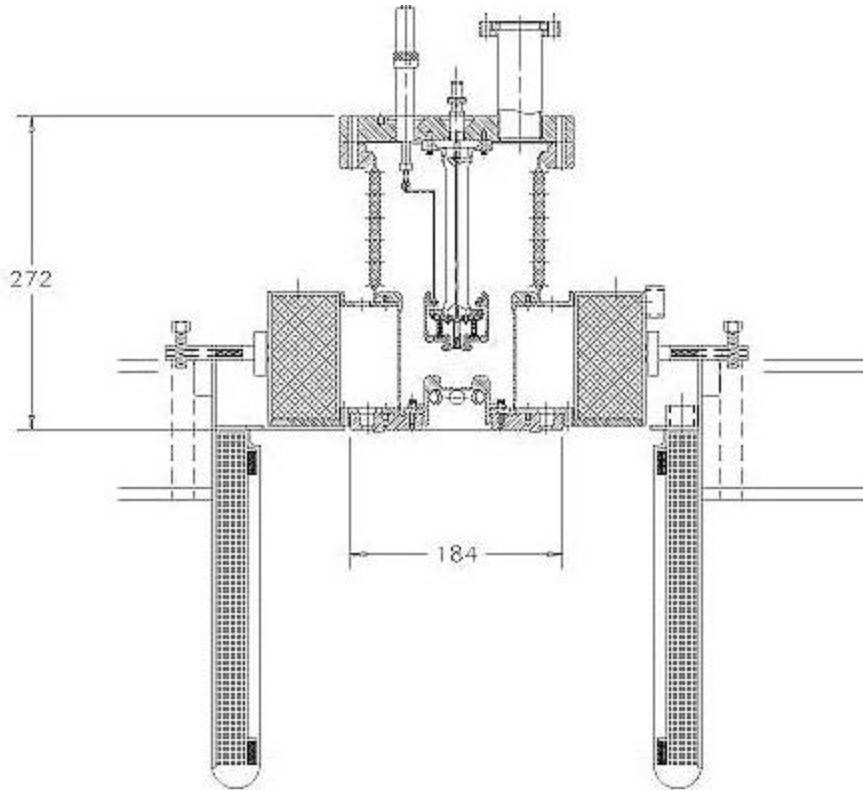
- Angular momentum dominated beam transport
  - Beam transport optics from the exit of the gun solenoid to the entrance of the cooling section is dictated by three beam properties:
    - (1) A large emittance-like contribution from the angular momentum
$$\varepsilon_N = eBr_c^2 / (2mc^2).$$
For  $B = 600$  G,  $r_c = 0.25$  cm,  $\varepsilon_N \approx 100$  mm-mrad
    - (2) Low beam aberrations
    - (3) High optics stability and reproducibility
- A 5-mm diam cathode gun immersion in a 200-G solenoid was successfully tested in 1999. No difference in the Pelletron stability was observed.
- Much theoretical work was done by Burov, Derbenev, Shemyakin and myself to understand the limits of such an optical scheme. A non-trivial and interesting optics theorem was proven. We named it “the generalized Busch’s theorem”. It states that in a general case of a non-axially symmetric beam transport from one round beam to another round beam state it is the absolute value of the angular momentum, which is conserved (and not the angular momentum itself, as in the classic Busch’s theorem).
- Beam line was fully designed and most of the elements were ordered.

# Electron gun and collector assembly



S. Nagaitsev, FNAL

# Electron Gun



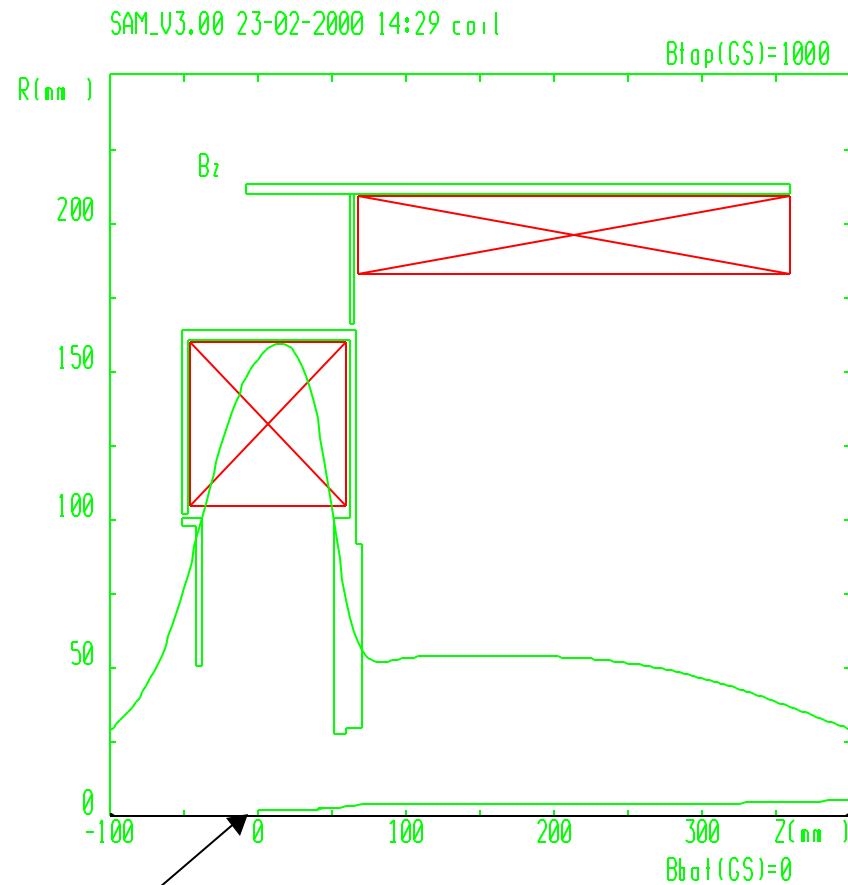
Gun assembly with solenoids



Cathode assembly mounted on a 200 mm OD flange.



# Magnetic field distribution in the gun

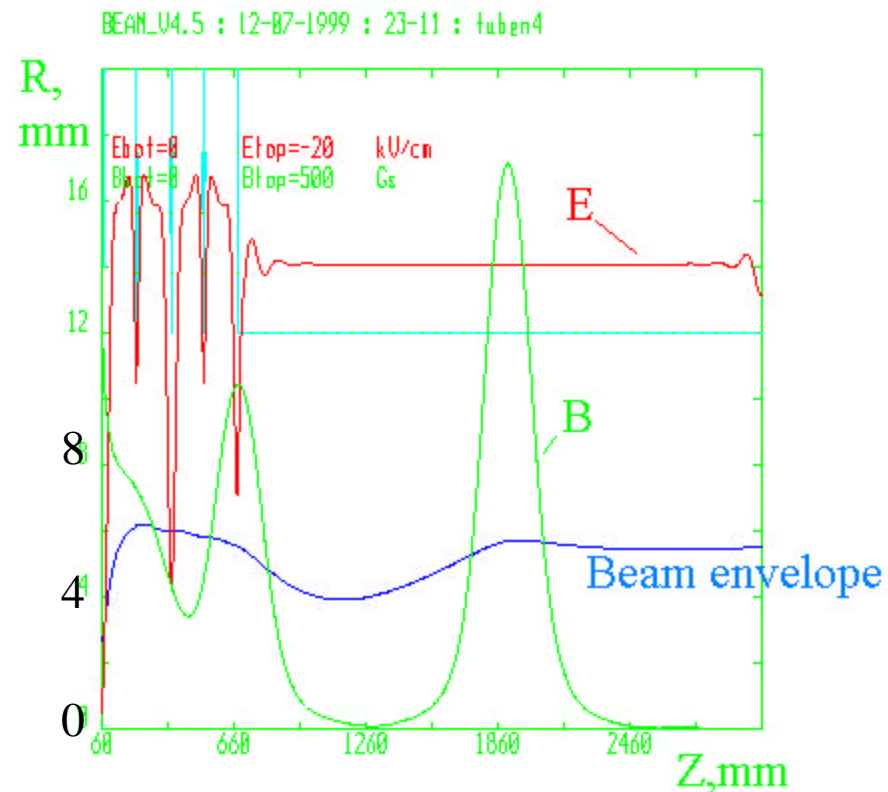


Cathode

Magnetic field at the cathode is 618 G.

S. Nagaitsev, FNAL

# Beam envelope in the acceleration tube

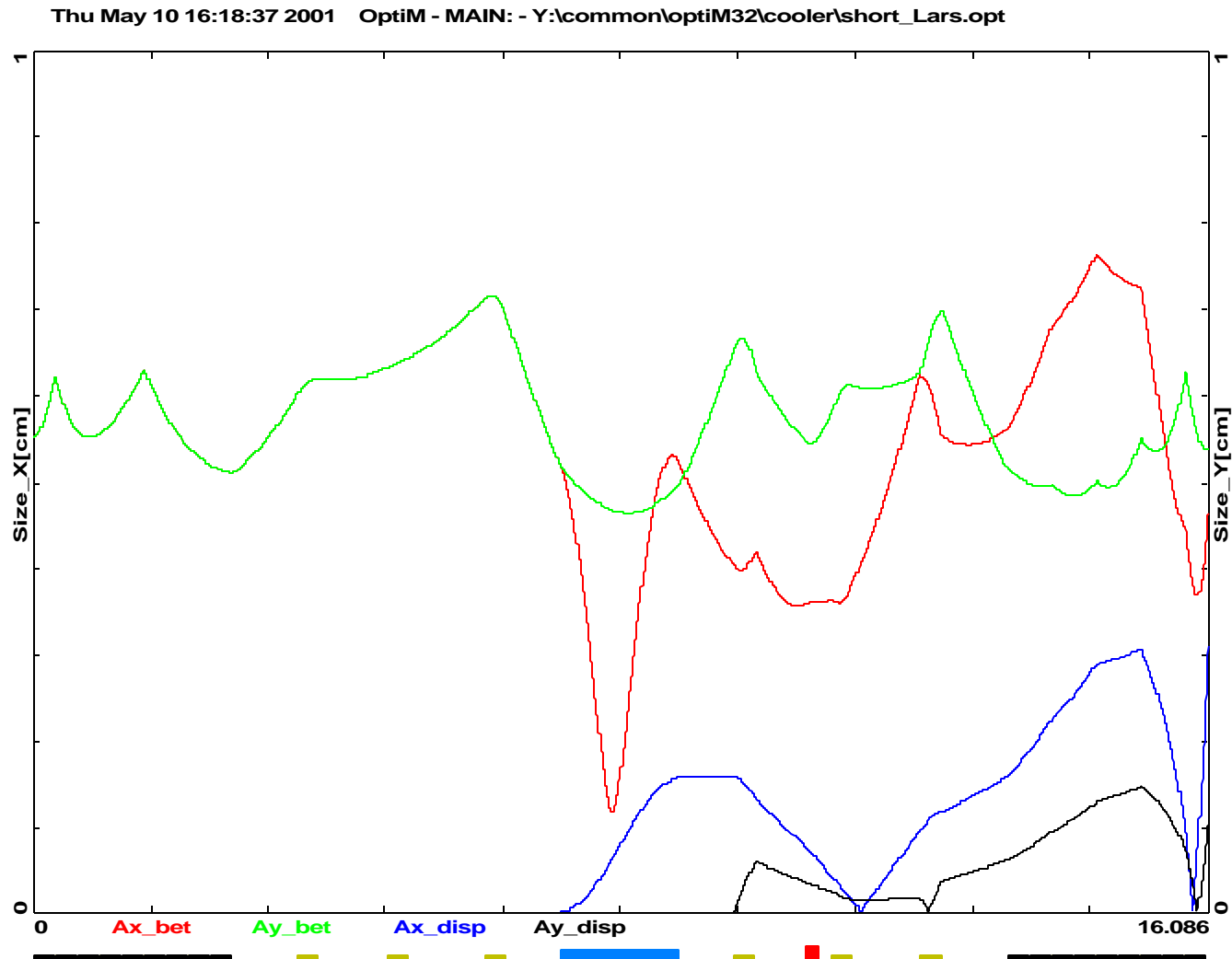


Beam envelope simulation.

$B_{\text{cath}} = 600 \text{ G}$ ,  $I_b = 1 \text{ A}$ ,  $U_0 = 4.3 \text{ MeV}$ .

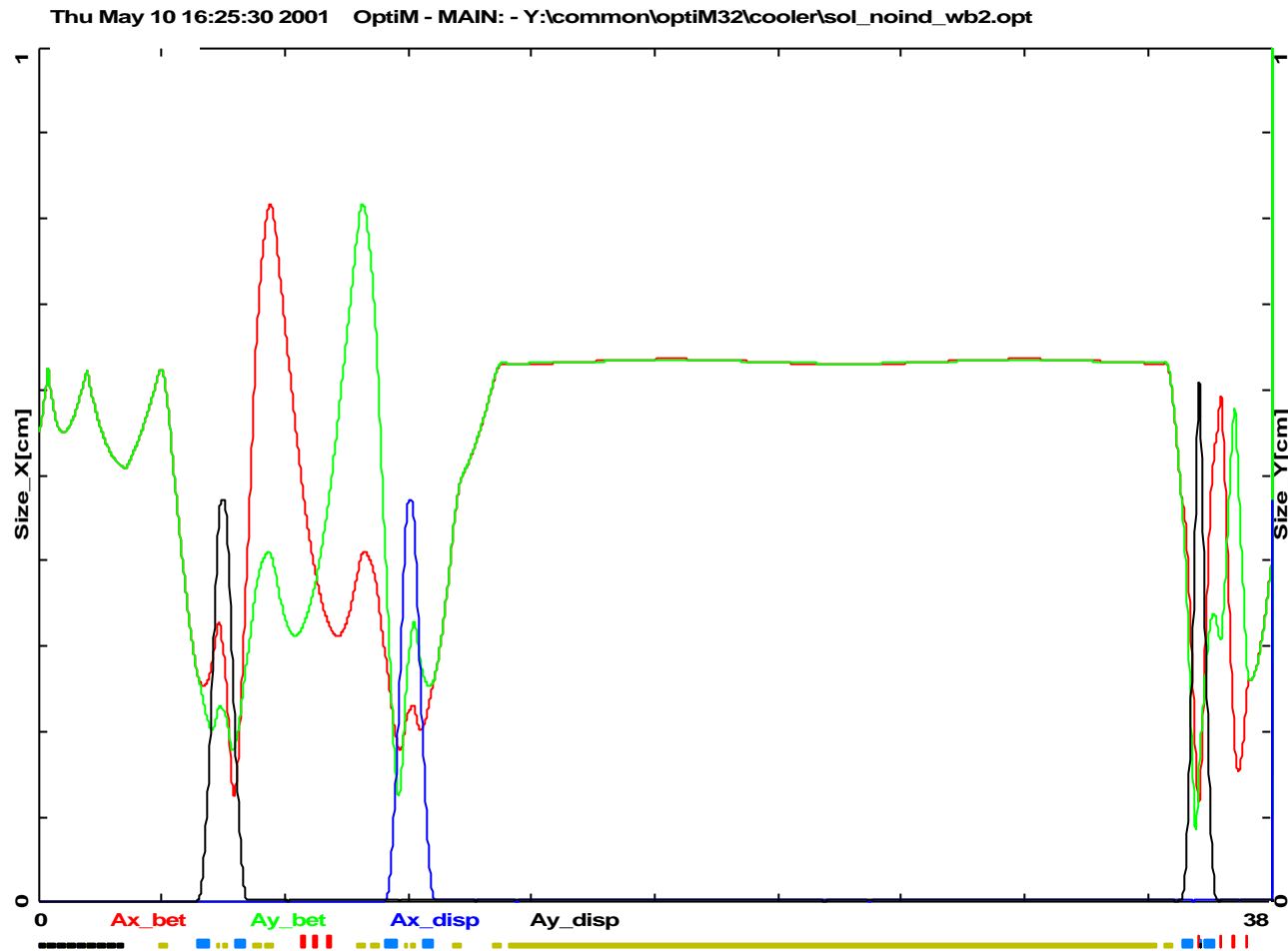
S. Nagaitsev, FNAL

# Beam envelope in a short U-bend channel



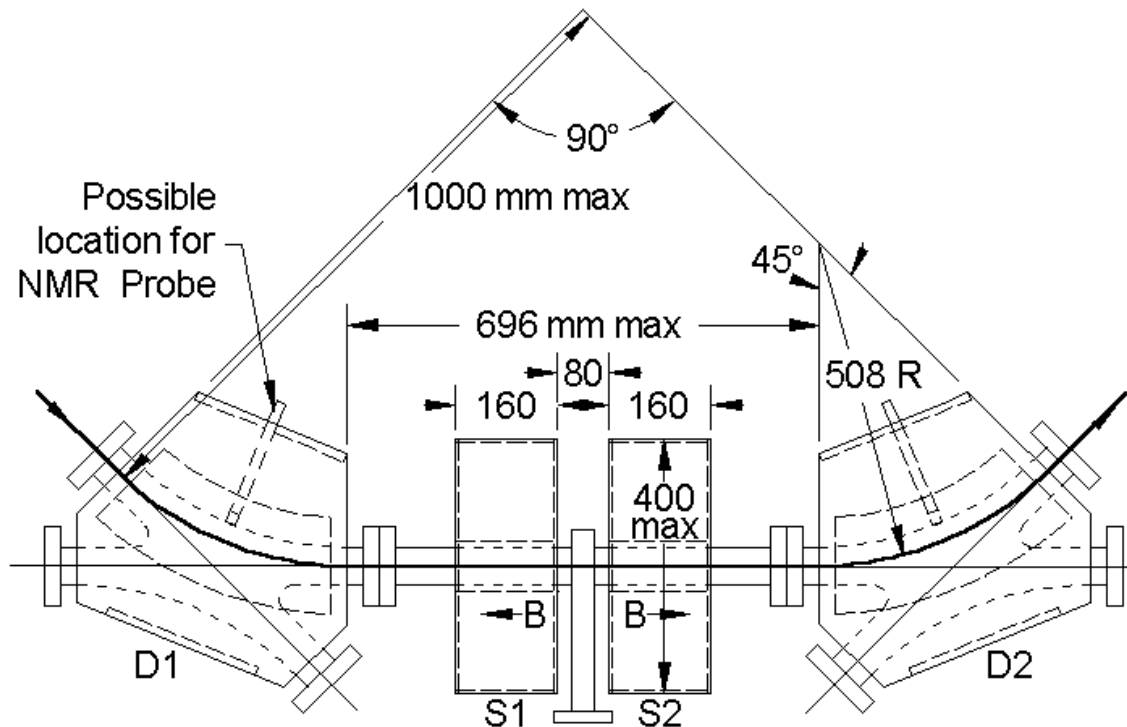
S. Nagaitsev, FNAL

# Beam envelope in a full-scale beamline



S. Nagaitsev, FNAL

# Beam line elements



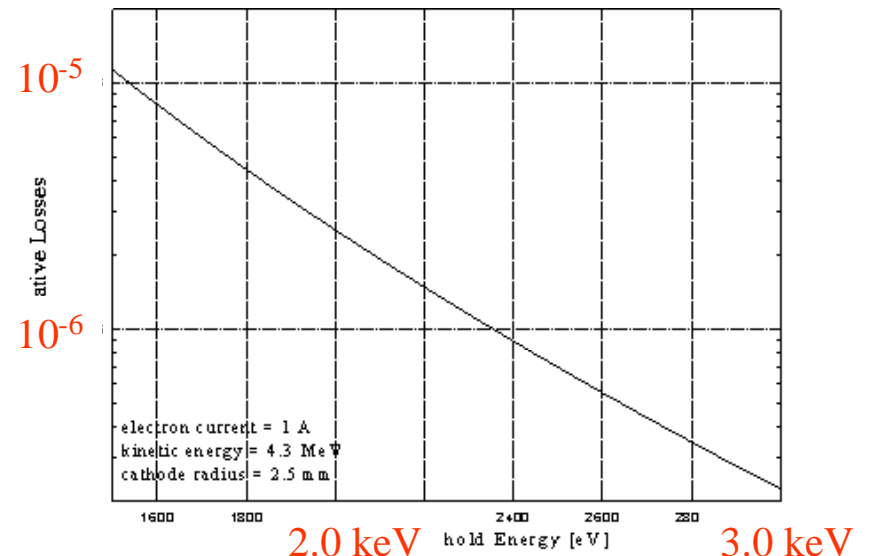
A 90-degree dispersion-free bend is made of two NMR-regulated dipole magnets and two opposing-field solenoids. All mounted on an adjustable frame and shielded by a mu-metal shield. AL vacuum chamber will be used.

All bends are ordered and are due in Jan., 2002

S. Nagaitsev, FNAL

# Energy Distribution in a Relativistic DC Electron Beam due to IBS

- IBS places a limitation on the minimum collector voltage,  $U_{coll}$ . To provide the acceptable level of losses, the value of  $U_{coll}$  should be above 2 kV.
- The rms energy spread of the beam due to the multiple IBS is below the acceptable limit for the electron cooling process.
- Tails of the multiple IBS Gaussian distribution are insignificant in comparison with the single large-angle IBS tails.
- Any beam size increase in the beam line regions with fixed focusing properties (such as bends) is beneficial for both the multiple and single IBS as it leads to a lower transverse temperature and lower beam density.



Relative population of high energy tails as a function of lab frame energy spread (keV).  
The electron beam current is 1 A, beam kinetic energy is 4.3 MeV, the cathode radius is 2.5 mm.

# Cooling section solenoid

- consists of 10 identical solenoids in series, divided by instrumentation gaps

Total length 20 m

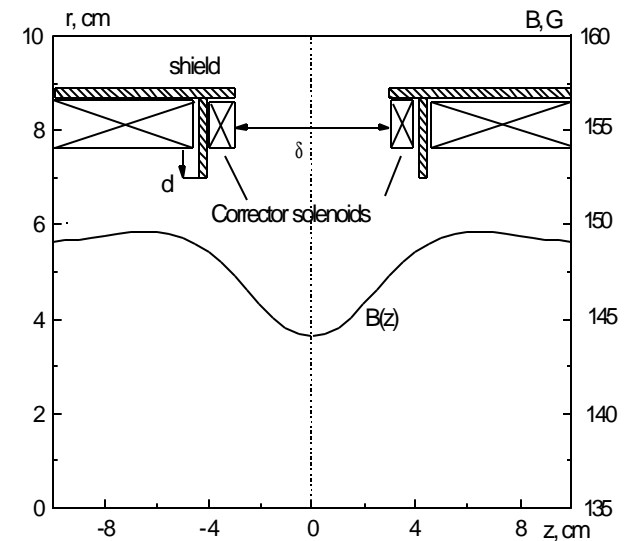
Magnetic field 50 - 150 G

Electron angles  
in the section  $< 0.1$  mrad

Integral of transverse  
magnetic field  $\leq 0.3$  G·cm

# Solenoid Overview

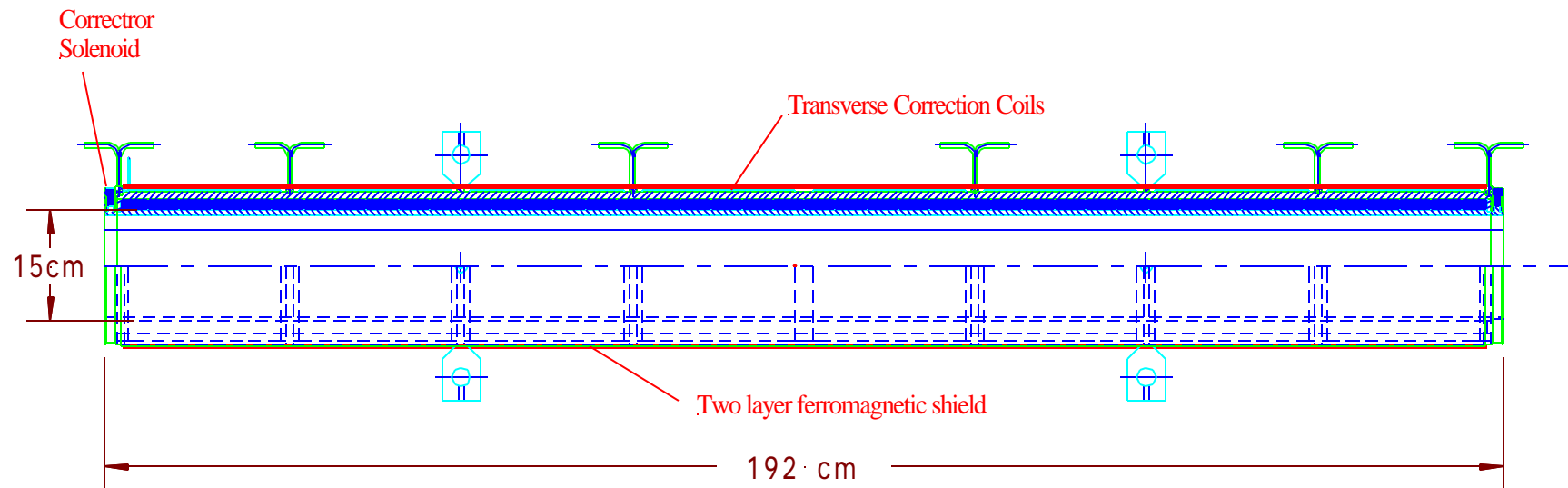
- Ten 2-m long modules connected in series
- Each module:
  - a solenoid (188 cm long), 4 A, 80 V, 150 G
  - two corrector solenoids to correct gap effects
  - 20 transverse correctors (may be eventually connected in series with the solenoid PS)
  - 8-cm long gap for instrumentation
  - shielding with a coefficient of at least 1000 to shield stray fields of about 5 G.
- Two prototype modules were produced, installed and measured. Their properties were found satisfactory. The production of 12 more improved modules has started at Fermilab. The rate of delivery is expected to be 2 solenoids/month.





## Parameters of the module solenoid

|                              |         |
|------------------------------|---------|
| Number of layers             | 6       |
| Number of turns in one layer | ~980    |
| Wire size (square AWG13)     | 1.88 mm |
| Current for $B = 150$ G      | 4 A     |
| Total weight                 | 250 kg  |
| Power                        | 240 W   |



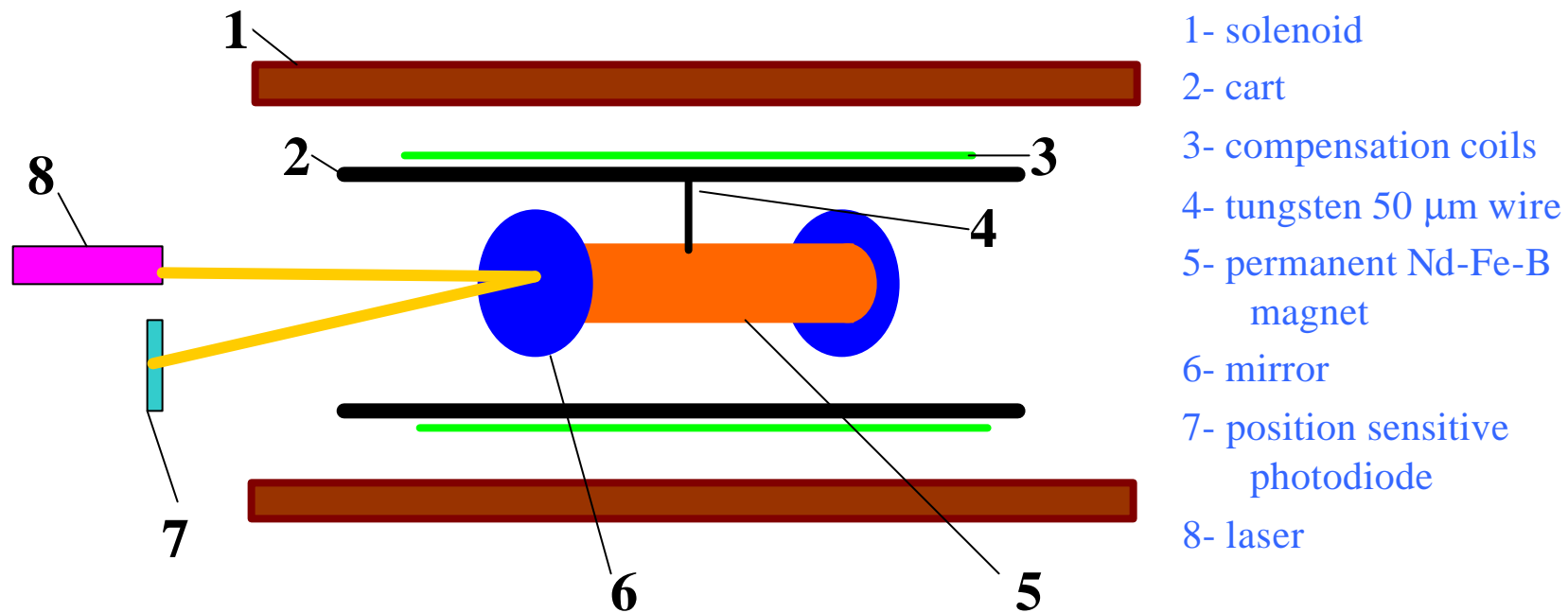
S. Nagaitsev, FNAL

## Two prototype cooling section solenoid modules installed



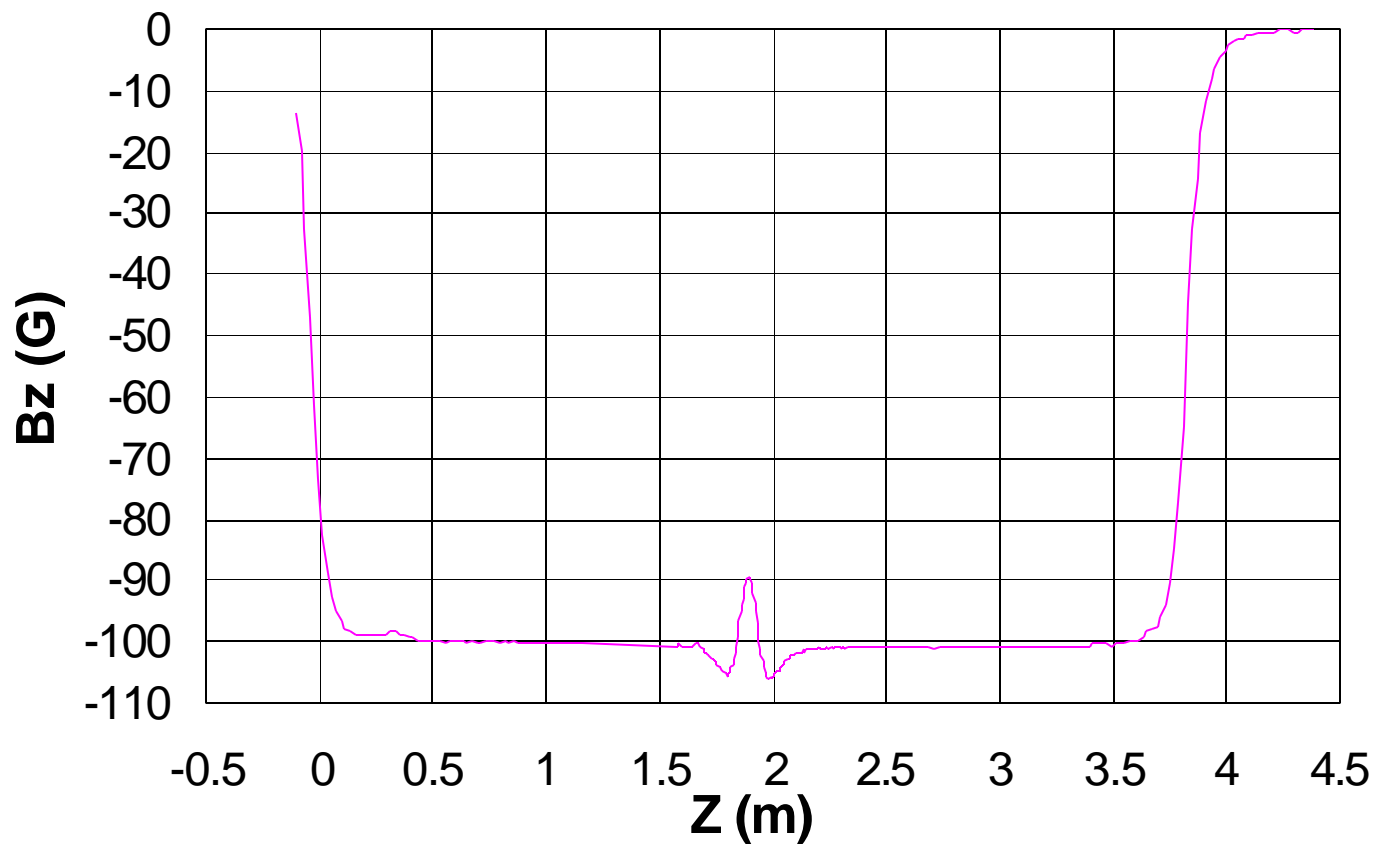
S. Nagaitsev, FNAL

# Compass-based magnetic field sensor (designed and built by Budker INP)



S. Nagaitsev, FNAL

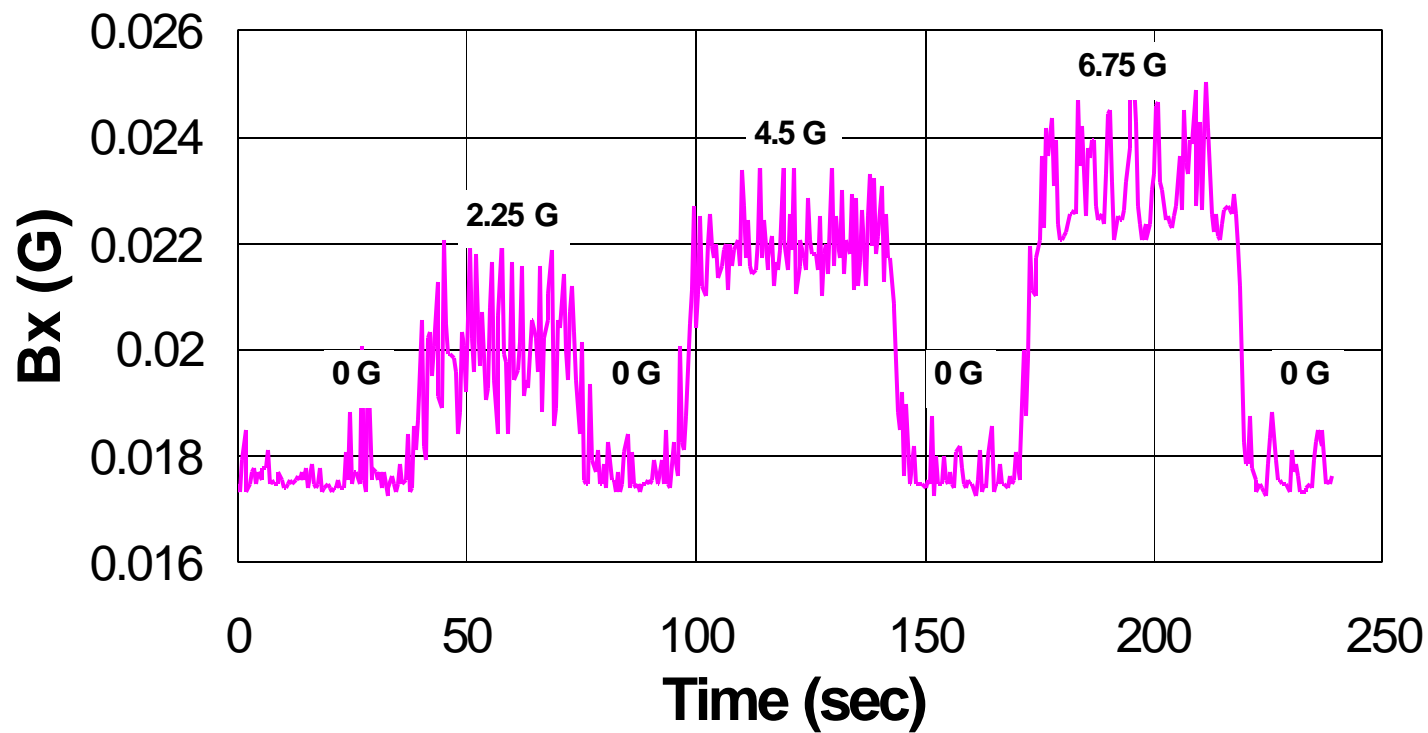
## Longitudinal magnetic field in two solenoid prototypes



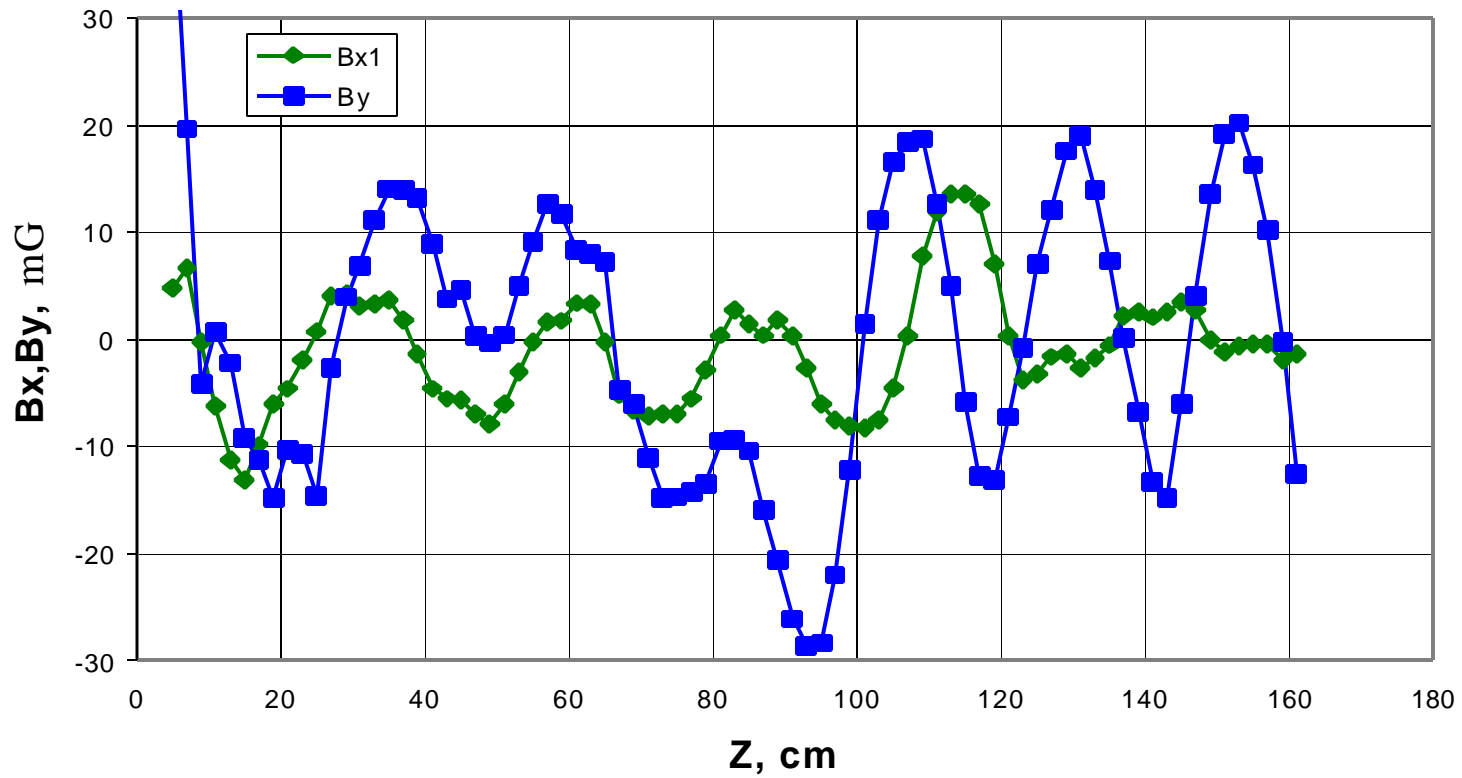
S. Nagaitsev, FNAL

### Shielding of external field.

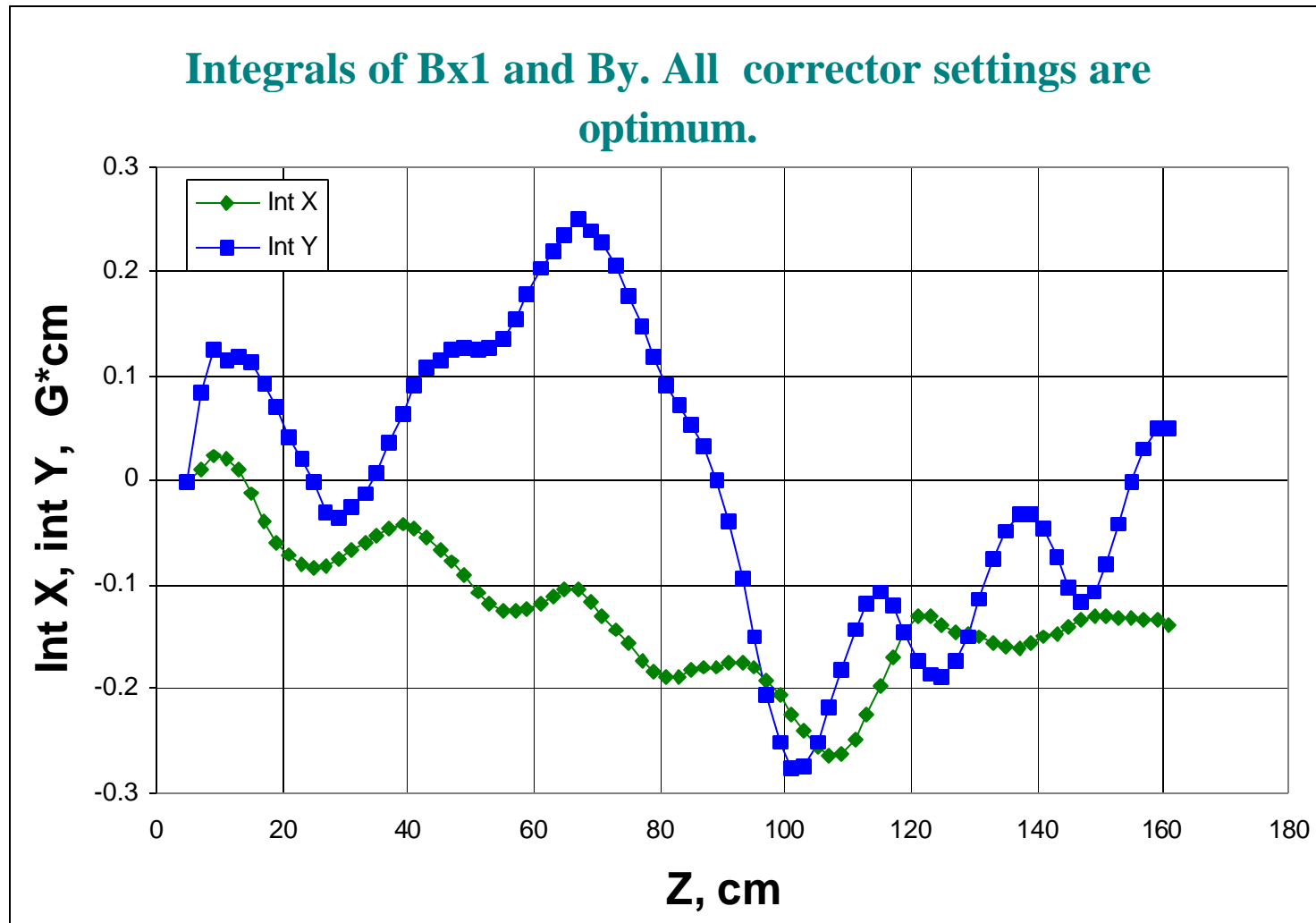
Magnitudes of external fields with no shields are presented above the curve.  $K_x \sim 950$ .



Transverse magnetic fields in solenoid #1,  $B_z = 50$  G  
Correctors are set to minimize the field integral



# Integral of transverse magnetic field



S. Nagaitsev, FNAL

# Final remarks

- The project suffered some delays but so did the Run II commissioning.
- We enjoy a strong support from the lab management. If all goes as planned, we are hoping to report about the installation in two years.



# Electron cooling collaboration

- **FNAL:** S. Nagaitsev (group leader), A. Burov, A. C. Crawford, V. Dudnikov, T. Kroc, V. Lebedev, J. Leibfritz, J. MacLachlan, M. McGee, F. Ostiguy, G. Saewert, C.W. Schmidt, A. Shemyakin, J. Volk, A. Warner
- **CEBAF:** Ya. Derbenev
- **IUCF**
- **Budker INP**
- **JINR**
- **National Electrostatics Corporation**